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Physics-Based Prognostics for Optimizing Plant Operation

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PHYSICS-BASED PROGNOSTICS FOR OPTIMIZING PLANT OPERATION

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Abstract: Scientists at the Pacific Northwest National Laboratory (PNNL) have examined the necessity for optimization of energy plant operation using "DSOM®c" – Decision Support Operation and Maintenance and this has been deployed at several sites. This approach has been expanded to include a prognostics component and tested on a pilot scale service water system, modeled on the design employed in a nuclear power plant. A key element in plant optimization is understanding and controlling the aging process of safety-specific nuclear plant components. This paper reports the development and demonstration of a physics-based approach to prognostic analysis that combines distributed computing, RF data links, the measurement of aging precursor metrics and their correlation with degradation rate and projected machine failure.[d]

Keywords: DSOM®; Prognostics

Introduction:

Component failures run the gamut from mildly annoying, (e.g., a leak in a compressed air line), to disastrous, as in the stuck open pressurizer relief valve at Three-Mile Island. In all such events a price is to be paid in terms of the economic penalty paid in lost revenue resulting from component replacement (downtime, maintenance hours and parts), a loss in production reliability (schedule impingement), or the public perception of the safety of the process itself.

There is a compelling need to provide new and improved measurement science and technology, together with appropriate methodologies, for the analysis, monitoring, protection and management of the nation's critical infrastructure. Many critical systems face threats as a result of random acts, including terrorism, and threats that result from degradation caused by the effects of aging.

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[a] From February 1, 2005, Director, Center for Advanced Energy Studies, Idaho National Laboratory.
[b] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RLO 1830.
[c] DSOM® is a registered trademark of Battelle Memorial Institute.
[d] This work was performed with the support of the U.S. Department of Energy's (DOE's) Nuclear Energy Research Initiative (NERI) and PNNL's Laboratory Directed Research and Development (LDRD) funding.

Much of the critical civil infrastructure in the US is rapidly approaching, or in some cases has already passed, its original design life. The total replacement cost for all aging systems that are found in the national critical infrastructure – including the electrical power system, oil and gas production and storage, transportation and water supply – is enormous and far beyond reasonable levels of expenditure for "on-time" replacement [1].

Producing an improved methodology for optimizing asset lifetime productivity was a direct result of plant operations and maintenance (O&M) experience being applied in a research environment to develop and quantify the fundamental communications and diagnostics relationships between the necessary O&M functional elements of an operating process plant [2].

Diagnostics: understanding the problem and its root cause.

The DSOM® system was designed to diagnose plant problems and provide the operations, maintenance, engineering, training and administrative (termed OMETA) agents necessary to allow the formulation of each of these five plant perspectives in a software model. The DSOM® program aims to improve the communication linkages necessary to facilitate the information flow that each element needs to cope with process plant operational problems.

Prognostics: understanding component stressors and the rate of process and material degradation that will result in a future failure.

Stressors are defined as those physical conditions that would cause a specific degradation mechanism to be active such as *low inlet pressure* causing fluid cavitation in a pump or *high temperature* causing a rapid drop in electrical insulation resistivity. The DSOM® physics-based approach to prognostics is really a conjunction and codification of several well accepted and related facets of the O&M world [2].

A First Principals Approach to Prognostics:

Condition-based maintenance (CBM) stressor-based analysis is based on understanding which stressor characteristics provide an early indication for mapping subsequent damage resulting from a degradation mechanism. The resulting physical damage and the associated decrease in asset performance start with the application of a stressor to the component. The design engineer sets the desired stressor intensity level so the degradation in the physical state of the component happens slowly enough for the equipment to last for a specified design life. In general, when the design limit of a stressor is exceeded, during operation, the component life expectancy starts to shorten to less than the projected design duration. Conversely, careful control of operational parameters can extend the component life beyond that normally expected for the design failure point.

The premise of the prognostic methodology is that, by not trending a performance metric per se, but by focusing on trending the stressor characteristics, a relationship can be derived that will allow a much more accurate projection of the remaining useful life. Figure 1 shows the expected result in narrowing the uncertainty by keying on the stressor itself.

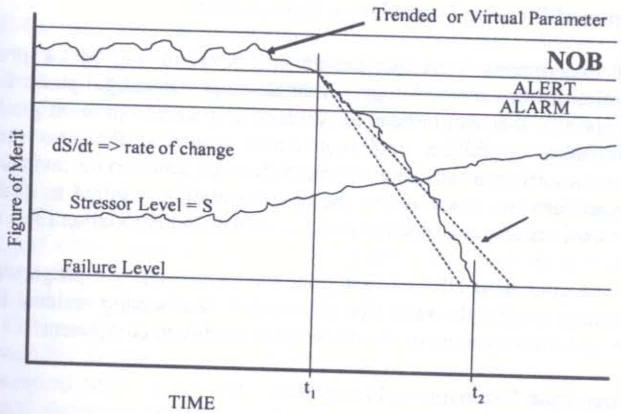

Fig. 1. Stressor Measurement Effect on Prediction Uncertainty

In the trend analysis example above, the slope of the trended parameter is thought to give a measure of the degradation rate of the component performance. This is assumed to be a function of the rate of decline in the physical characteristics of the equipment as well. Experience from measurements has shown this assumption to be true if one accounts for the nonlinearity between physical attributes and their effects on performance [2].

In the stressor-based analysis, the instantaneous degradation rate can be correlated to the stressor intensity by a functional relationship. This can then be taken one step further, to:

$d^2P/dt^2 = dS/dt$, which is nothing more than stressor trend or slope (1)

So by following the slope of the stressor intensity, we have a precursive measure of the rate of change in the performance degradation. Thus, the stressor slope can be used to predict and to refine the path of the performance vector.

The rate of change in the stressor slope gives an even more sensitive precursive dimension for narrowing the uncertainty of the predicted performance path. This stressor gradient (termed the root precursive indicator) is the most sensitive time-linked correlation from stressors through to failure.

$d^2S/dt^2 \Rightarrow$ Root Precursive Indicator (2)

If a measure of this root indicator can be accurately determined, each level in the derivative chain can be integrated to provide an accurate physical description of the future condition and performance of the component. It also follows that as diagnosticians, our quest is a complete mathematical description of the stressor's derivative chain – its level, slope and gradient.

Formulation of Stressor-Degradation Correlations:

A set of experiments were performed at PNNL to provide a proof of principal demonstration for this methodology. A single-stage centrifugal pump was chosen as the active component that would bear the greatest impact on common production facilities. By examination of failure and root cause histories, the two most predominant mechanisms resulting in centrifugal pump failure are found to be cavitation and vibration. Careful consideration was given to the instrumentation required to quantify appropriate stressor intensities and examine the physical effects of degradation [2].

The ultimate goal is to allow a first principles approach to a prognostic algorithm that will accurately predict the reduction of impeller and bearing residual life as a result of cavitation and misalignment of the driver from its driven component.

Pump Cavitation Experimental Results:

The initial goal for the cavitation test series was to characterize the operational data as well as the spatial and spectral nature of the cavitation produced in a single stage centrifugal pump. To this end, highly accurate operational instrumentation was used to measure the motor current; suction pressure and temperature; and the discharge pressure, temperature and flow. Specialized acoustic sensors were then installed in the test pump. These sensors were placed in direct contact with the pumped fluid to provide a clear view of the acoustic energy impacting the wall of the volute.

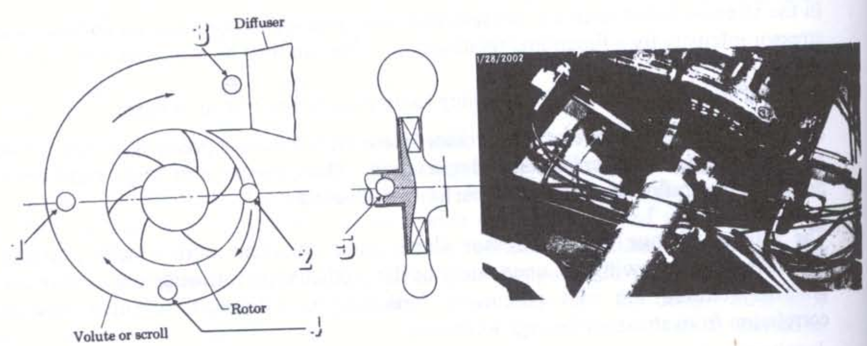

Fig. 2. Initial Acoustic Sensor Placement.

Acoustic emission (AE) techniques [3] were used in an attempt to detect incipient cavitation and to quantify the spectral and spatial (source location) intensity of the degradation mechanism they present. The objective was to not only show that AE can be used to detect the vapor implosion acoustic signals, but to discriminate cavitation intensity from signals generated by the mechanical and fluid noise in the pumping system.

To accomplish this end, an array of Pinducer VP-1093 acoustic emission sensors were placed in the pump suction and volute (pressure recovery) sections to map acoustic impingement intensity. Special plugs were drilled and the sensors were epoxied into the plug without metal-to-metal contact. The depth of sensor extension was gauged to place the active tip at the exact flow stream interface (flush with the pump casing interior wall). These transducers are miniature piezoelectric crystals specified to have a frequency response of 0 (DC) to ~1.2 MHz. Five separate pre-amplifiers and amplifiers were connected to a LeCroy LT374M digital oscilloscope. Each transducer was sampled from 0 to 400 MHz, and a filter used to remove system noise. The resulting spectra were then compared and correlated to the physical degradation observed at each location during the course of an extended cavitation run. Severe electromagnetic interference was experienced. Comparison tests were then performed on a process pump that was not driven by a variable frequency drive (VFD), and a clear cavitation signature was obtained. Subsequent trials on our test pump were performed following removal of the VFD, and spectral signatures were obtained for both direct fluid contact and contact with the exterior surface of the pump volute. Highest values of signal-to-noise ratio were obtained using a non-intrusive probe located near the suction of the pump, as shown in Figure 3.

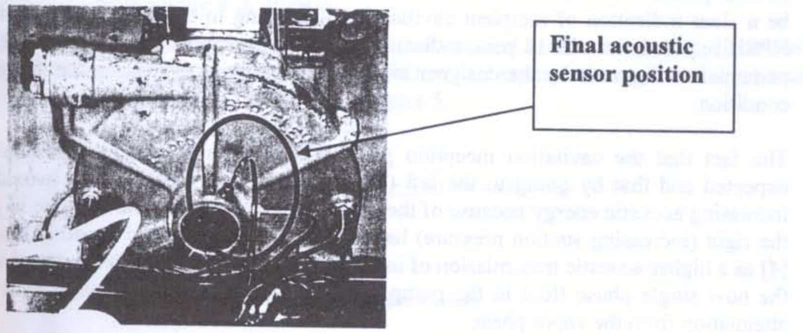

Fig. 3. Surface Mount Position of Acoustic Probe.

Cavitation Analysis:

Once the measurement hurdles were overcome, it remained to quantify the cavitation stressor intensity and to perform a long duration run so that the physical degradation effects could be determined. Before degradation testing could commence, a series of tests was performed to characterize the operational and experimental acoustic measurement system response to cavitation and to develop a methodology for quantifying stressor intensity. Initially the primary circulation pump and associated valving were configured to produce the design net positive suction head plus 10 psi. Subsequent runs performed by reducing the suction pressure in 2-psi increments, produced a clear acoustic cavitation pattern in the 30 to 55 kHz range.

To make intuitive sense from this data, the baseline (no cavitation) curve was used to normalize, the data sequences to produce a positive acoustic value in association with increasing cavitation. Additionally, following normalization, the 30 to 55 kHz interval was integrated for each run to capture the overall nature of the incident acoustic energy. The quantification of this incident acoustic bandwidth as a function of the pump suction pressure produced the curve characteristic shown in Figure 4.

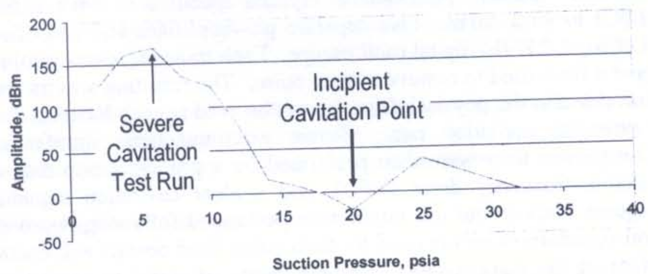

Fig. 4. Cavitation Intensity as a Function of Suction Pressure.

Several points should be noted from this curve. The inflection point at 20 psia appears to be a clear indication of incipient cavitation. According to the pump manufacturer, the NPSH requirement was 18 psia, indicating either an incorrect pump characterization or perhaps a willingness by the designer to allow the pump to operate in a mild cavitation condition.

The fact that the cavitation inception point is a minimum acoustic signal would be expected and that by going to the left (decreasing suction pressure) one would expect increasing acoustic energy because of the increase in cavitation. The increase in going to the right (increasing suction pressure) has logically been explained by other researchers [4] as a higher acoustic transmission of inherent pump noise caused by the "hardening" of the now single phase fluid in the pump casing. Basically, this is caused by a lack of attenuation from the vapor phase.

A maximum acoustic energy signal is seen at about 6 psia, below which it was observed that very low pressures produce a slug flow phenomena that again reduces the acoustic coupling to the casing and reduces the impacting energy level. This correlates well with slug flow observations in the Lexan suction pipe of our test rig at these pressures.

A continuous cavitation run was initiated and continued for 4 weeks, with the exception of a 4 hour power outage. The test pump was then secured, drained and disassembled to obtain wear readings relative to the baseline. With the exception of the wear ring clearances, very little metal removal was observed. The impeller to volute gap (wear ring) did indicate a 10-mil increase in clearance.

As a result of the extensive troubleshooting and test apparatus modifications that were necessitated by the unanticipated difficulty in establishing a satisfactory acoustic signal, only 4-weeks remained following the acoustic baseline characterizations. Without performing further experiments, only a simple linear correlation can be derived from the available two point wear data set. When combined with the acoustic intensity measurement, this gave us a "zeroth order" approximation to a deterministic correlation that relates suction differential pressure to incipient cavitation (the primary stressor) and ultimately the degradation rate of the pump.

The data from the slope of the logarithmic increase of acoustic signal with increasing pressure drop from cavitation inception was used to produce a cavitation-damage correlation. Making several assumptions about the validity of our logarithmic intensity scale and of its relationship to metal removal rate, we derived an equation of the form

$$MRR = K[10\exp(13.9x(PSID_{NPSH}))] \tag{3}$$

where MRR is the metal removal rate (in mils)

$PSID_{NPSH}$ is the differential pressure between the operating point and the pump NPSH limit

K is a material and geometric constant dependent on the specific pump

The coefficient 13.9 is the slope of the (logarithmic) acoustic intensity line from Figure 4 in db/psid.

It is suggested by the literature [2] that the metal removal rate is not, in fact, linear with time given constant cavitation intensity, but follows an asymptotic exponential approach to a limiting degradation rate, as shown in Figure 5.

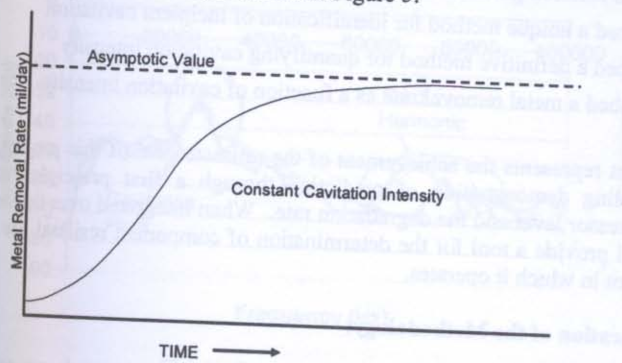

Fig.5. Suggested metal removal rate at constant cavitation intensity.

This variable rate is explained by observing the cavitation shock front initially as it impinges on a relatively smooth metal surface, and it is difficult for even a high velocity (shock) wave to create sufficient impulse to remove metal particles from the surface. As time goes on, the gradual pitting of the surface causes a roughening effect that allows better "purchase" for shock fronts to cause removal by more direct impact on the metal fragments. Once a fully roughened surface is created, the fragment removal rate approaches a constant value.

When combined with the available acoustic intensity measurements, this gives us an approximation to a deterministic correlation relating suction pressure differential to the actual degradation rate of the pump casing. Making several assumptions about the validity of the logarithmic intensity scale and the linearity of its relationship to metal removal rate, we can come up with a final equation of the form -

$$MRR = \underbrace{K10^{a\Delta P+b}}_{\substack{\text{Pump Design}\\ \text{Pump Material}\\ \text{Cavitation Intensity}}} \underbrace{e^{(\Delta P \div D)t}}_{\text{Damage Factor}} \tag{4}$$

The constants K, a, b, and D are dependent on pump-and case-specific inputs as noted above.

In conclusion, this cavitation experimental test run has:

- Identified the "active" cavitation frequency range
- Provided location guidance for cavitation acoustic measurement
- Developed a unique method for identification of incipient cavitation
- Developed a definitive method for quantifying cavitation intensity
- Established a metal removal rate as a function of cavitation intensity.

This final bullet represents the achievement of the ultimate goal of this project in that it gives an enabling demonstration of prediction through a first principles correlation between the stressor level and the degradation rate. When integrated over the component lifetime, it will provide a tool for the determination of component residual life based on the environment in which it operates.

A Field Application of the Methodology:

Following completion of the laboratory cavitation development work, an opportunity presented itself to attempt to extend the theory to an industrial application. A large hydro-electric dam reported severe pump cavitation with evident surface vortices in their auxiliary service water (ASW) pumps. Their engineering staff requested the laboratory team apply the damage prognostic technique to define the intensity of the cavitation, the expected damage rate and the expected residual life of the pumps.

Machinery and Measurements Description:

The three ASW pumps are of a low-head axial flow line-shaft design. These large capacity pumps find uses in many applications such as irrigation and flood control where their rugged design and reliability are a requisite. The pump's 7 foot diameter "propeller" is driven by a 450-Hp 6-pole induction motor (1100) through a single reduction gear reducer (8.5:1) via a 46-foot drive shaft. The oxygenated water from the discharge of these pumps is directed to a location near the entrance to the dam's fish ladder to act as an attractant to enhance salmon migration up the ladders.

The vane axial or propeller pump is the most sensitive pump to hydraulic instabilities caused by flow conditions at its inlet [5]. Following replacement of the ASW pumps to increase in their capacity by 50%, unacceptable hydraulic instabilities in the pump sump region were observed and later verified by hydraulic modeling. Because modifications to the existing sumps would be expensive and the result would still be outside the recommended Hydraulic Institute design criteria, pump prognostic expertise from the Pacific Northwest National Laboratory was sought in an attempt to quantify the life factor reduction that would result from operation under the existing conditions.

Following the procedure demonstrated in the laboratory, tri-axial vibration and acoustic emission signals were obtained by epoxying the transducers directly to the pump casing. The amplified signal was then fed to the high speed oscilloscope, where a fast Fourier transform (FFT) was produced from the time serial data. A ten-fold sampling of the FFT was used to present a representative trace of the acoustic spectrum. The acoustic traces for all three AWS pumps have been compiled and are presented in Figure 6. A clear cavitation "bulge" is seen in the acoustic signature for all three pumps.

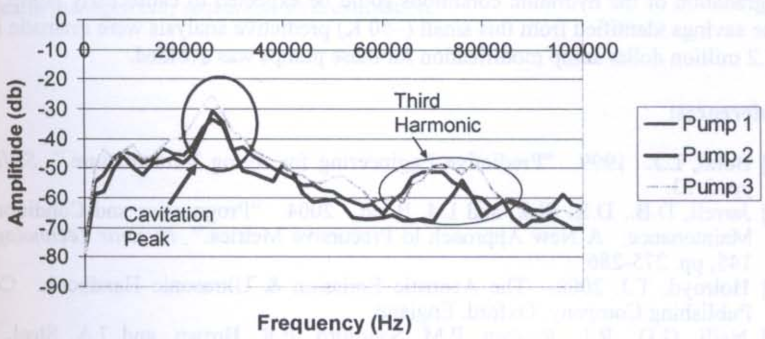

Fig. 6. Cavitation Spectral Indication.

To accurately quantify the cavitation intensity would require a reference non-cavitation state measurement. Lacking that, an estimate based on laboratory operational experience was used to evaluate the energy potential found in the cavitation peak. A comparison of integrated energy and the height of the peak values will then allow an extrapolation from the laboratory degradation values [6] to what might be expected for wear rates in the field. A complicating factor is the large distance that separates the primary cavitation site (the propeller tip) and the acoustic sensor. The vertical flow does act to sweep the collapsing bubbles toward our sensors. The result of all these caveats is that an uncertainty estimate of ± 50% must be placed on the resulting damage rate.

It is expected, based on the above discussion and knowledge of the propeller materials (ASTM A242 steel), that the cavitation wear rate under the conditions found at the time of testing will be limited to approximately 5 ±3 mils (thousandths of an inch) of metal per year. This is a fairly mild cavitation situation and by itself would lead to pump failure in approximately 78 years, thus it does not significantly impair the life expectancy of the pump. Further flow impediment caused by debris collection on the sump trash rack could, however, change this condition dramatically leading to much higher rates of degradation.

Conclusions:

The physics-based prognostic methodology has been demonstrated both in the laboratory and at a dam. The economic impact of the approach is clearly seen in the dam study.

The existence of cavitation and sump-wall vortices has been confirmed in the dam AWS pumps. Degradation in the impeller from cavitation is not expected to be excessive nor lead to dramatic shortening of pump life. It is probable, however, that the pump output is somewhat less than the expected flow because of the reduced efficiency of the impeller. Quantification of the flow reduction would not be possible without additional measurements. Additionally, increases in vibration severity induced by further degradation of the hydraulic conditions could be expected to cause early pump failures. The savings identified from this small (~50 K) predictive analysis were dramatic in that a $1.2 million dollar sump modification for these pumps was avoided.

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